Inertial control of the VIRGO Superattenuator[1]

Giovanni Losurdo* for Pisa and Florence VIRGO Groups

**Istituto Nazionale di Fisica Nucleare - Sezione di Pisa*
Via Livornese 1291 - 56010 - S.Piero a Grado (Pisa) - Italy
e-mail: losurdo@galileo.pi.infn.it

Abstract. The VIRGO superattenuator (SA) is effective in depressing the seismic noise below the thermal noise level above 4 Hz. On the other hand, the residual mirror motion associated to the SA normal modes can saturate the dynamics of the interferometer locking system. This motion is reduced implementing a wideband (DC-5 Hz) multidimensional control (the so called *inertial damping*) which makes use of both accelerometers and position sensors and of a DSP system. Feedback forces are exerted by coil-magnet actuators on the top of the inverted pendulum. The inertial damping is successful in reducing the mirror motion within the requirements. The results are presented.

I INTRODUCTION

The test mass suspension of the VIRGO detector, the superattenuator (SA) [1], has been designed in order to suppress the seismic noise below the thermal noise level above 4 Hz. The expected residual motion of the mirror is $\sim 10^{-18}$ m$\sqrt{\text{Hz}}$ @4 Hz. At lower frequencies, the residual motion of the mirror is much larger (~ 0.1 mm RMS), due to the normal modes of the SA (the resonant frequencies of the system are in the range 0.04-2 Hz).

To lock the VIRGO interferometer the RMS motion of the suspended mirrors must not exceed 10^{-12} m (to avoid the saturation of the read-out electronics). VIRGO locking strategy is based on a hierarchical control: feedback forces can be exerted on 3 points of the SA (inverted pendulum (IP) [2], *marionetta* and mirror). The control on the 3 points is operated in different ranges of frequency and amplitude. The maximum mirror displacement that can be controlled from the marionetta without injecting noise in the detection band is ~ 10 μm. Therefore, a damping of the SA normal modes is required for a correct operation of the locking system. An active control of the SA normal modes, using sensors and actuators on

[1] To appear in the Proceedings of the *Third E.Amaldi Conference on Gravitational Waves Experiments*, Caltech, Pasadena, 12-16 July 1999.

top of the IP, capable of reducing the mirror residual motion within a few microns, has been successfully implemented.

II EXPERIMENTAL SETUP

The setup (fig. 1) of the experiment is composed by a full scale superattenuator, provided with 3 accelerometers (placed on the top of the IP), 3 LVDT position sensors (measuring the relative motion of the IP with respect to an external frame), 3 coil-magnet actuators. The accelerometers work in the range DC-400 Hz and have acceleration spectral sensitivity $\sim 10^{-9}\ \mathrm{m\,s^{-2}\,Hz^{-1/2}}$ below 3 Hz [3]. The sensors and actuators are all placed in *pin-wheel* configuration. The sensors and actuators signals are elaborated by a computer controlled ADC (16 bit)-DSP-DAC (20 bit) system. The DSP allows to handle the signals of all the sensors and actuators, to recombine them by means of matrices, to create complex feedback filters (like the one of fig. 5) with high precision poles/zeroes placement and to perform a large amount of calculations at high sampling rate (10 kHz). The suspended mirror is provided with an LVDT to measure its displacement with respect to ground.

III THE CONTROL STRATEGY

The active control of the SA normal modes is defined *inertial damping*, because it makes use of inertial sensors (accelerometers) to sense the SA motion. The advantage of using accelerometers is that they perform the measurement with respect to the "fixed stars", while position sensors do it with respect to a reference frame which is not seismic noise free. Therefore, inertial sensors are to be used so that no seismic noise is reinjected by the feedback. Actually, in the real SA control both sensors are used: position sensors provide a low frequency (DC - 10 mHz) control of the SA position (in order to avoid drifts), while accelerometers allow a wideband reduction of the noise in the region of the SA resonances (10 mHz - 2 Hz).

The object to control is a MIMO (multiple in-multiple out) system: each sensor (accelerometer/LVDT) is sensitive to the 3 modes (X,Y,Θ) of the IP and each actuator excites all the modes. To simplify the control strategy the sensors outputs and the actuators currents are digitally recombined to obtain independent SISO (single in-single out) systems (fig. 2): the system is described in the normal modes coordinates (for a description of the diagonalization procedure see [5,6]). Each normal mode is associated to a so called *virtual sensor* (sensitive to that mode and "blind" to the others) and to a *virtual actuator* (acting on one mode only, leaving the others undisturbed). In this way one is able to implement independent feedback loops on each d.o.f., greatly simplifying the control strategy. Fig. 3 shows the output of the virtual accelerometers X and Θ. In the X plot, the 40 mHz resonance of the IP translation mode and all the modes of the SA chain are visible (as pole/zero structures). In the Θ plot, only the rotation mode of the IP is visible. The two plots show that different feedback strategies have to be implemented on

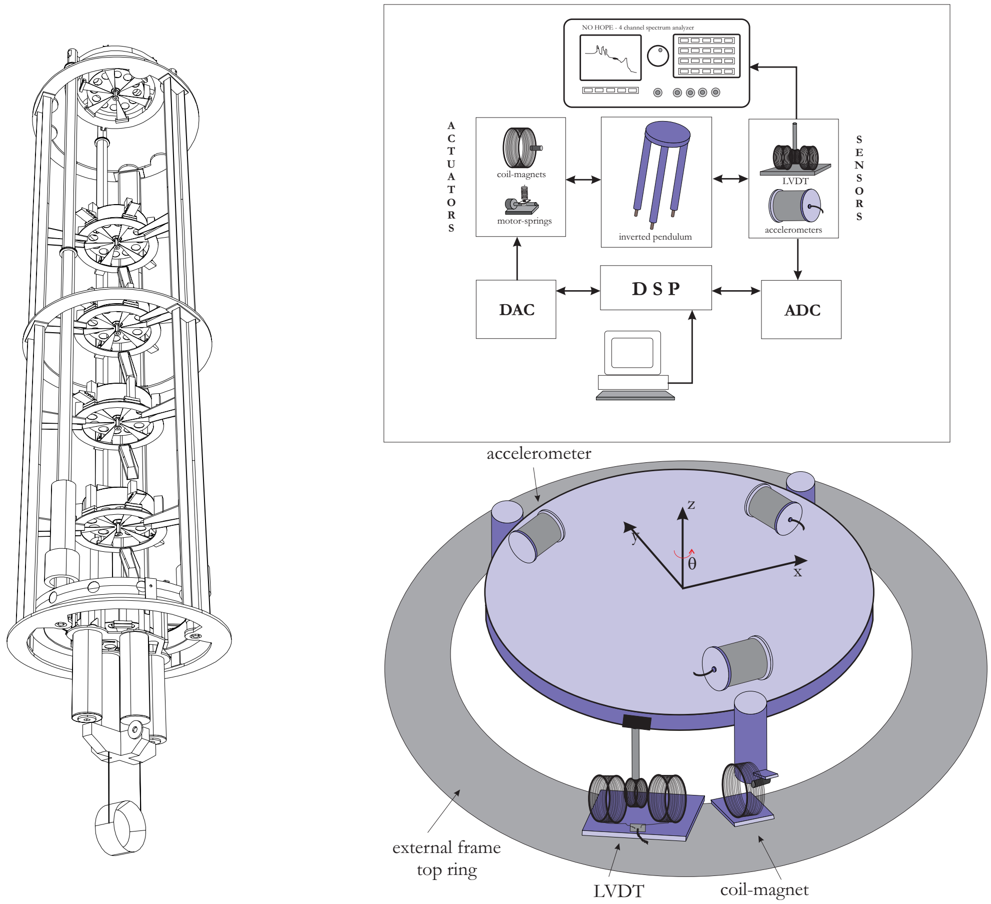


FIGURE 1. LEFT: the superattenuator; RIGHT TOP: logical scheme of the setup for the local active control; RIGHT BOTTOM: simplified view of the IP top table, provided with the 3 accelerometers. One LVDT position sensors and one coil-magnet actuator are also shown.

the different d.o.f.. The basic idea of inertial damping is to use the accelerometer signal to build up the feedback force. Actually, if the control band is to be extended down to DC, a position signal is necessary. Our solution was a *merging* of the two sensors: the virtual LVDT and accelerometer signals are combined in such a way that the LVDT signal ($l(s)$) dominates below a chosen cross frequency f_{merge} while the accelerometer signal ($a(s)$) dominates above it (see fig. 4 and ref. [4]). The feedback force has the form[2]:

$$f_{\mathrm{fb}} = G(s)\left[a(s) + \epsilon l(s)\right] \tag{1}$$

where $G(s)$ is the digital filter transfer function (see fig. 5) and ϵ is the parameter whose value determines f_{merge}. We have chosen $f_{\mathrm{merge}} \sim 10$ mHz (corresponding

[2] Actually, the LVDT signal $l(s)$ is properly filtered in order to preserve the feedback stability at the cross frequency and in order to reduce the amount of reinjected noise at $f > f_{\mathrm{merge}}$.

to $\epsilon \sim 5 \cdot 10^{-3}$). This approach allows to stabilize the system with respect to low frequency drifts at the cost of reinjecting a fraction ϵ of the seismic noise via the feedback.

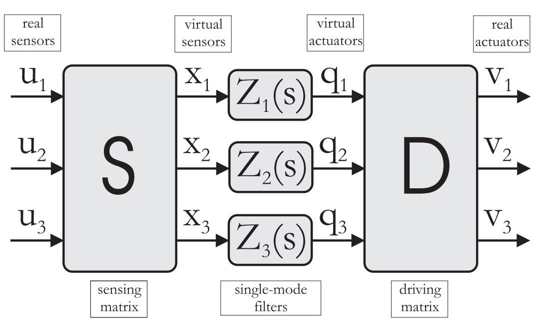
IV INERTIAL CONTROL PERFORMANCE

The result of the inertial control (on 3 d.o.f.) is shown in figure 6. The measurement has been performed in air. The noise on the top of the IP is reduced over a wide band (10 mHz - 4 Hz). A gain > 1000 is obtained at the main SA resonance (0.3 Hz). The RMS motion of the IP (calculated as $x_{\mathrm{RMS}}(f) = \sqrt{\int_f^\infty \tilde{x}^2(\nu)\mathrm{d}\nu}$) in 10 sec. is reduced from 30 to 0.3 μm. The closed loop floor noise corresponds to the fraction of seismic noise reinjected by using the position sensors for the DC control and can, in principle, be reduced by a steeper low pass filtering of the LVDT signal at $f > f_{\mathrm{merge}}$ and by lowering f_{merge}: both this solution have drawbacks and need a careful implementation.

Preliminary measurements of the displacement of the mirror with respect to ground have been performed in air, using an LVDT position sensor. The residual RMS mirror motion in 10 sec. is[3]:

$$x_{\mathrm{RMS}}(0.1\,\mathrm{Hz}) \leq 3\ \mu\mathrm{m}. \tag{2}$$

[3] This number has been obtained with a feedback design less *aggressive* then the one of fig. 5: the gain raised as $1/f$, the cross frequency was 30 mHz and no compensation of the dips was needed.



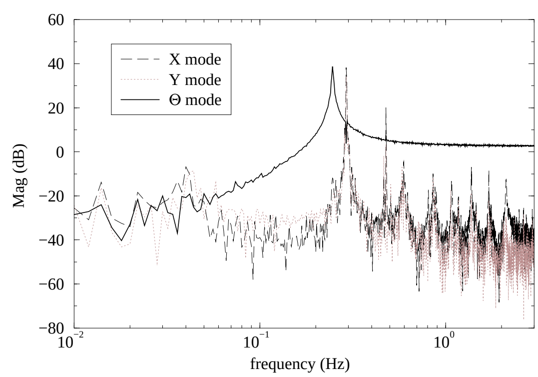


FIGURE 2. LEFT: The logic of the diagonalisation: the output u_i of the sensors are linearly recombined by a matrix **S** in order to produce 3 *virtual* sensors outputs (x_i), sensitive to pure modes. Three independent feedback filters $Z_i(s)$ are designed for the pure modes and 3 generalized forces q_i are produced. The q_i are turned into real currents (v_i) to feed the actuators via the matrix **D**. RIGHT: Effect of the digital diagonalization: the 3 modes are uncoupled, the Θ mode is excited.

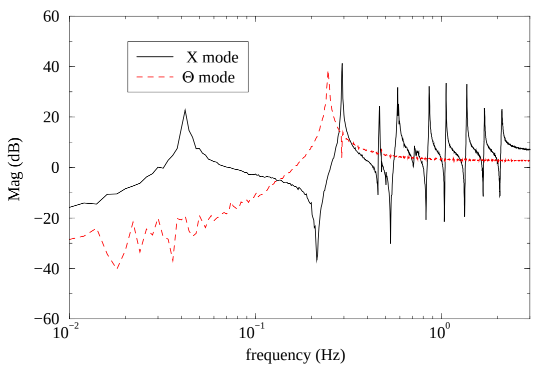


FIGURE 3. The output of the virtual accelerometers X and Θ are compared. Different feedback strategies are required for the two modes

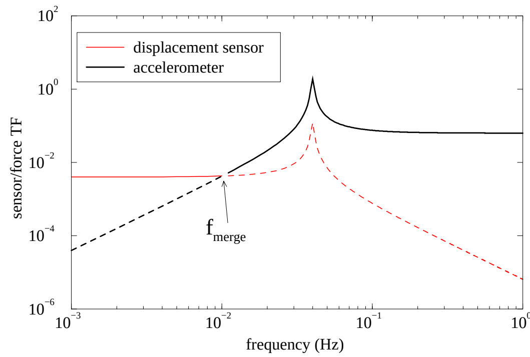


FIGURE 4. *Merging* of displacement and acceleration sensors (simulation for a simple pendulum).

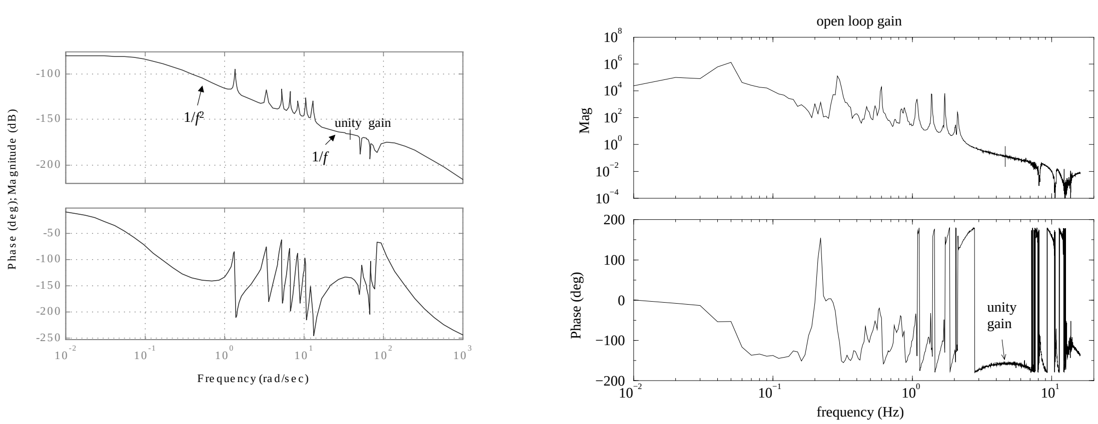
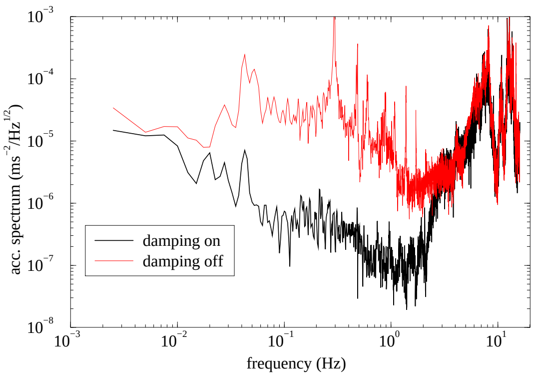


FIGURE 5. LEFT: Digital filter used for the inertial damping of a translation mode (X). The filter slope is f^{-2} in the range 10 mHz< f <3 Hz, f^{-1} for f >3 Hz. The unity gain is at 4 Hz. The peaks in the digital filter are necessary to compensate the dips in the mechanical transfer function (see the transfer function of the X mode in fig. 3). RIGHT: open loop gain function (measured). The phase margin at the unity gain frequency is about 25°.



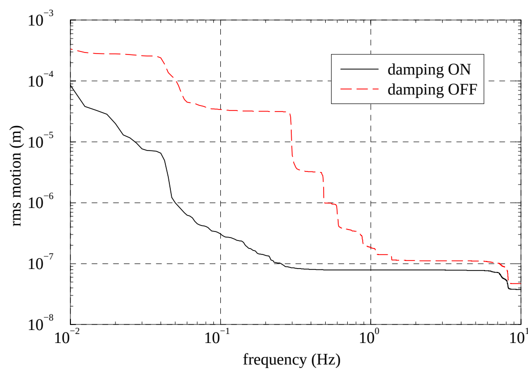


FIGURE 6. Performance of the inertial control (X, Y, Θ loops closed) of the superattuenuator, measured on the top of the IP: the left plot shows the acceleration spectral density as measured by the *virtual* accelerometer X (translation). The right plot shows the effect of the feedback on the RMS residual motion of the IP as a function of the frequency.

When the damping is on such a measurement can provide only an upper bound because the LVDT output is dominated by the seismic motion of the ground.

V FURTHER DEVELOPMENTS

Several ways of improving the inertial damping performance have been identified:

- a steeper low pass filtering of the LVDT output above $f_{\rm merge}$ may reduce the amount of reinjected seismic noise. In doing this one has to be careful to preserve proper phase difference between the LVDT and accelerometer signals;
- the lower $f_{\rm merge}$ the smaller the amount of reinjected noise. Lowering $f_{\rm merge}$ is difficult due to the mechanical tolerance on the parallelism of the IP legs: if the legs are not perfectly parallel, the top table tilts slightly as it translates. Therefore, the accelerometer signal is dominated by the tilt below 15-20 mHz, making thus impossible to use the accelerometers at very low frequencies. A technique for subtracting the effect of the tilt (using the information provided by the displacement sensors) has been defined and used to obtain the results here described [7]. Cancelling the tilt effect down to ~ 5 mHz makes us able to use the accelerometers down to 10 mHz [7]. Stricter requirements on the IP legs machining and improvements in the tilt subtraction technique may allow a lower cross frequency.

REFERENCES

1. F.Frasconi, *et al.*, Performances of the R&D superattenuator chain of the VIRGO experiment, to be published in the proceedings of the *XXXIVth Rencontres de Moriond*

(1999).
2. G.Losurdo, *et al.*, *Rev. Sci. Instrum.*, **70** (5), 2507-2515 (1999).
3. S.Braccini, *et al.*, *Rev. Sci. Instrum.*, **66** (3), 2672-2676 (1995).
4. S.J.Richman, J.A.Giaime, D.B.Newell, R.T.Stebbins, P.L.Bender, J.E.Faller, *Rev. Sci. Instrum.*, **69** (6), 2531 (1998).
5. A.Gennai, *et al.*, *A control model for the inverted pendulum*, VIRGO Note VIR-TRE-PIS-4900-102 (1997).
6. G.Losurdo, *Ultra-low frequency inverted pendulum pre-isolator for the VIRGO test mass suspension*, PhD Thesis, Scuola Normale Superiore, Pisa (1998).
7. A.Gennai, G.Losurdo, A.Marin, D.Passuello, *Inertial damping of the superattenuator*, VIRGO Note VIR-TRE-PIS-4900-104 (1999).